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Analysis of urban greenhouse gas dispersion within downtown Montréal using computational fluid dynamics and field measurements

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SUMMARY

With urban regions contributing significantly to greenhouse gas (GHG) and pollutant emissions, we investigate the complex dispersion dynamics of these emissions for the downtown region of Montréal, Canada, using computational fluid dynamics. We initialize and validate these models with field campaign measurements from aircrafts, radiosondes, drones. GHG sensors, and a lidar wind profiler. An investigation of boundary conditions and atmospheric stability effects is carried out. Dispersion characteristics of carbon dioxide and methane emissions from McGill University's power plant, large government buildings, and vehicles are evaluated, with predictions compared to drone and rooftop measurements. These findings suggest that while traffic emissions contribute significantly to local GHG concentrations, other emission sources are missing from the model. Despite this, the prediction of carbon dioxide compares favorably to mean satellite measurements. Additional issues related to air quality are also analyzed.

Keywords: *computational fluid dynamics, greenhouse gases, pollutant dispersion, air quality, atmospheric stability*

1. INTRODUCTION

As urban areas continue to become home to an ever-growing majority of the world's population (Ritchie et al., 2025), emissions of greenhouse gases (GHGs) and air pollution are leading to significant effects on climate and human health. Carbon dioxide (CO_2) and methane (CH_4) are two important GHGs frequently emitted in due to human activities, with urban area as hotspots in particular. Air polluting byproducts, including ozone (O_3) and particulate matter of a diameter less than 2.5 µm ($PM_{2.5}$), are associated with the sources of these emissions, such as the burning of fossil fuels. As such, cities often face dangerously low air quality, with almost 9 million people dying due to air pollution each year (Lelieveld et al., 2019). By studying the emissions and subsequent dispersion of these GHGs and pollution, we may analyze their characteristic distributions across urban environments to foster healthier and more sustainable cities.

One method of doing this is with computational fluid dynamics (CFD), whereby the Navier-Stokes equations governing fluid flow are solved numerically. Within the two main branches of CFD, large eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) simulation, both have been shown to properly reproduce urban dispersion dynamics when initialized correctly (Gousseau et al., 2010). Due to the significantly higher computational demand needed to calculate turbulence in LES approaches, RANS simulations, which parameterize all turbulence and only generate mean flow fields, are often chosen to model complex phenomena. RANS simulations do require selection of a turbulence model, as well as defining a value for the turbulent Schmidt number controlling turbulent diffusion, both of which are known to dramatically affect accuracy (Franke et al., 2007; Tominaga and Stathopoulos, 2007). A prior urban wind flow and dispersion study for downtown Montréal showed skillful predictions with the standard k-ε turbulence model and a turbulent Schmidt number equal to 0.6 (Dyer-Hawes et al., 2024). Very few CFD studies focusing on the dispersion of GHGs in full-scale cities exist, as greater attention is given to the dispersion of air pollutants (Gousseau et al., 2010). One of the limited existing studies, Toja-Silva et al. (2017), considered the dispersion of CO_2 from power plant in Munich, Germany. The RANS based approach used the Durbin modified k-ε turbulence model, finding good agreement with a ground-based instrument measuring column-averaged dry-air mole fractions of CO_2. The present study aims to combine field measurements with an urban CFD model to simulate the dispersion of GHGs in downtown Montréal, assessing the role of thermal stratification which is often neglected in CFD simulations. Besides importance for sustainable and healthy cities, an accurate dispersion model also makes it possible to validate retrievals of GHG concentrations from satellites and to further pinpoint emission sources (Streets et al., 2013).

2. DATA AND METHODOLOGY

In coordination with the CFD model developed, a multi-platform measurement campaign was performed on 21 February 2024. These measurements were conducted to assess the spatiotemporal variability GHGs in Montréal and serve as initialization and validation of the model. A lidar wind profiler and Picarro GasScouter installed on the roof of McGill University's Burnside Hall provided validation data from wind velocity and CO_2 and CH_4 concentrations. At 08:00 EST (UTC-05:00, with all times after given in EST) drone measurements were taken at McGill University's Gardner Hall, sampling CO_2 and CH_4 concentrations at ground level, 30, 60, 90, and 120 m above ground level (AGL). Gault Nature Reserve, 40 km east of the city of Montréal, was the location of an upper air sounding launched at 09:00. Lastly, a Twin Otter aircraft operated by the National Research Council Canada flew over the Montréal region, including a missed-approach maneuver 10 km east of the city, surveying vertical profiles of atmospheric conditions and CO_2 and CH_4 concentrations. Profiles of background conditions from the sounding and aircraft enabled the accurate initialization of the CFD model.

This study then uses two types of solvers within the CFD model, examining the impact of different initialization conditions and compressible effects. The simulations were run with the open-source CFD software OpenFOAM, with the mesh generated with SnappyHexMesh. The computational domain was created using terrain and building models provided by Ville de Montréal. This domain follows the best practice guidelines established in Franke et al. (2007), with buildings and topography placed far enough from the boundaries of a cylindrical domain 1.7 km in height and 8 km in diameter, ensuring that the flow fully develops. A cylindrical domain with 36 sides was necessary to reproduce a rotating wind direction with height observed in both the sounding and aircraft measurements. The inlet and outlet faces are split horizontally and rotate with height. The first simulations are performed with the incompressible RANS solver simpleFoam, using either initial wind speed and direction profiles measured by the sounding or the aircraft's missed-approach at CYHU. The standard k-ε turbulence model is used and the measured wind speed profile is assigned to the domain inlet. Both turbulent kinetic energy (k) and the dissipation rate (ε) were calculated according to Weerasuriya et al. (2018). Once suitable initial conditions were determined, the compressible version of the solver, rhoSimpleFoam, was run to include thermal stratification effects resulting from the temperature inversion present on the day. GHG emissions are modeled from three sources, including the McGill University power plant, large government buildings, and vehicles. The power plant's natural gas usage for the day is estimated, from which an emission rate of CO_2 and CH_4 is calculated. Emissions from government buildings are treated similarly, while vehicle emissions use the average traffic flow rate separated by vehicle class to estimate emission rates. With the mean wind field predicted by the models, these emission sources are then included to simulate dispersion. Background concentrations of CO_2 and CH_4 measured by the aircraft are defined across the inlet. Finally, both CO_2 and CH_4 are treated as passive scalars, as no chemical reactions or deposition processes are included in the model.

3. RESULTS AND DISCUSSION

The day simulated featured a moderately strong low-level jet (LLJ), with a maximum wind speed of 18.6 m s^{-1} at 425 m AGL, with wind decreasing above this height. Given slight differences in the wind profiles recorded by the aircraft and radiosonde, both measurement sources were used to initialize incompressible simulations, revealing that initialization with the sounding profile led to better agreement with measurements within the downtown region from the lidar. While both the incompressible and compressible solver were able to accurately reproduce the LLJ profile, the compressible solver reduces the maximum wind speed leading to better agreement. This is likely due to the compressible model predicting higher turbulence intensity, suggesting increased mixing near the level of the jet peak.

With GHG emissions then included in the model, the incompressible solver was found to skillfully predict the concentration of CO_2 measured by the Picarro GasScouter on the roof of Burnside Hall. The 30-minute average recorded concentration at 09:00 was 475.0 ppm with a standard deviation of 5.51 ppm, while the incompressible solver predicted a concentration of 478.8 ppm. When including thermal effects with the compressible solver, this concentration prediction decreases to 426.4 ppm. This is found to be the results of the temperature inversion present on the day, suppressing the vertical transport of vehicle emissions to the roof of Burnside Hall. Figure 1 shows the spatial distribution of CO_2 1.75 m AGL as predicted by the incompressible and compressible solvers. These solvers predictions of CH_4 concentrations at the location of the Picarro GasScouter are significantly lower than the measured concentration (1.948 ppm and 1.870 ppm respectively compared to 2.116 ppm ± 0.0124 ppm). This mainly relates to the fact that the primary sources of CH_4 in urban areas (landfills and natural gas distribution) are not implemented in these models, thus underpredictions are to be expected. Underpredictions remain in comparing modeled concentrations of CO_2 and CH_4 with the drone measurements. As the location of the drone flight was further away from the downtown core, there are fewer emission sources present nearby in the model. This points to the need for highly detailed emissions inventories, which the city of Montréal, among many others, lacks.

Using the modeled dispersion characteristics, we also analyze issues related to air quality. Average concentrations of CO_2 in sections of the domain are considered with respect to the urban density metrics of building area density and frontal area index, showing the influence of urban morphology on ventilation. A particular building complex is highlighted which has the potential to suffer degraded air quality due to nearby traffic emissions which would be associated with hazardous pollutants and $PM_{2.5}$. Finally, we compare vertical profiles of CO_2 to measurements from the OCO-2 satellite and show moderate agreement. This motivates the further use of CFD models in validating satellite measurements and the potential for source inversion studies.

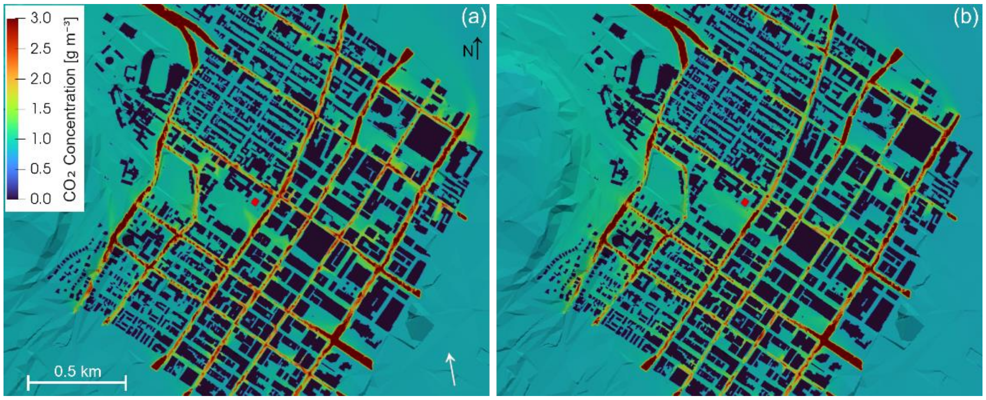

Figure 1: Predicted concentration of CO_2 1.75 m AGL by (a) incompressible solver and (b) compressible solver.

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